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Comparative study of energy saving light sources

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ABSTRACT

Techno-economic performance comparison of compact fluorescent lamps (CFL) with light emitting diodes (LED), electrode less fluorescent lamps (EEFL), fluorescent tubes, incandescent bulbs, photovoltaic (PV) and fiber optic lighting systems was carried out in view of worsening power and energy crisis in Pakistan. Literature survey showed 23 W CFL, 21 W EEFL, 18 W fluorescent tube or 15 W LED lamps emit almost same quantity of luminous flux (lumens) as a standard 100 W incandescent lamp. All inclusive, operational costs of LED lamps were found 1.21, 1.62. 1.69, 6.46, 19.90 and 21.04 times lesser than fluorescent tubes, CFL, EEFL, incandescent bulbs, fiber optic solar lighting and PV systems, respectively. However, tubes, LED, CFL and EEFL lamps worsen electric power quality of low voltage networks due to high current harmonic distortions (THD) and poor power factors (PF). Fluorescent lamps emit UV and pollute environment by mercury and phosphors when broken or at end of their life cycle. Energy consumption, bio-effects, and environmental concerns prefer LED lamps over phosphor based lamps but power quality considerations prefer EEFL. CFL and EEFL manufacturers claim operating temperatures in range of $-20\,^{\circ}\mathrm{C} < T_{CFL} < 60\,^{\circ}\mathrm{C}$ and $-30\,^{\circ}\mathrm{C} < T_{CFL} < 50\,^{\circ}\mathrm{C}$ but CFL frequently damage in wet and damp locations. Costs of low THD and high PF CFL, EEFL and LED lamps may be five to ten times higher that high THD and low PF lamps. Choice of a lamp depends upon its current THD, PF, life span, energy consumption, efficiency, efficacy, color rendering index (CRI) and associated physical effects. This work proposes manufacturing and user level innovations to get rid of low PF problems. Keeping in view downside of phosphor based lamps our research concludes widespread adoption of LED lamps. Government and commercial buildings may consider full spectrum hybrid thermal photovoltaic and solar fiber optic illumination systems.

Contents

1. Compact fluorescent lamps

Compact fluorescent lamps (CFL) have emerged as a potent alternative of incandescent lamps (bulb) due to lower power consumption and longer life. Lighting loads in homes and offices may vary from 25 to 30% of total domestic power consumption. A 23 W CFL produces same luminous efflux as a 100 W bulb. CFL consumes 2–5 times less power, lasts 8–10 times longer and saves \$30 (Rs2500/year) over its life compared to a bulb. 100 W bulb converts only 2.6% of power to white light whilst a CFL converts 6.6–8.8% of input power to white light. However, CFL produces distorted currents with current THD > 100% and low (0.47–0.67) PF leading to excessive utility energy losses [1]. Synergic effect of low power factor (0.457–0.67) CFL or switch mode power supplies

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(SMPS) would force utilities to supply 1.5–2.0 times more apparent power than the real loads. CFL requires high starting inrush currents and its harmonics cause additional I^2R losses due to increased system resistance at higher frequencies. It might cost about \$1–2 per CFL to add PF correcting circuit but the company might not be able to compete in market at least in underdeveloped countries. Recent low ($THD_I \leq 20$), medium ($20 < THD_I \leq 50$) and high ($THD_I > 50$) categorization helps guide the customers. CFL cost, depending on PF, THD and efficacy may vary from \$0.50 to \$55 [2]. Bad quality CFL may have 0.45 PF and 180% THD but a good CFL may have PF > 0.9 and THD < 20%. However, the PF correcting and THD mitigating circuits can reduce overall efficiency. Normally we say 40 W fluorescent tube but its magnetic ballast may consume additional 5–6 W power that is not reflected to customers, anyway. Chinese make CFL costs 3–4 times lower than the western technology based CFL. Utilities must test available CFLs and recommend the high PF and low current THD brands to reduce their reactive power losses. Circuit diagram and picture of modern CFL ballast is shown in Fig. 1 [3].

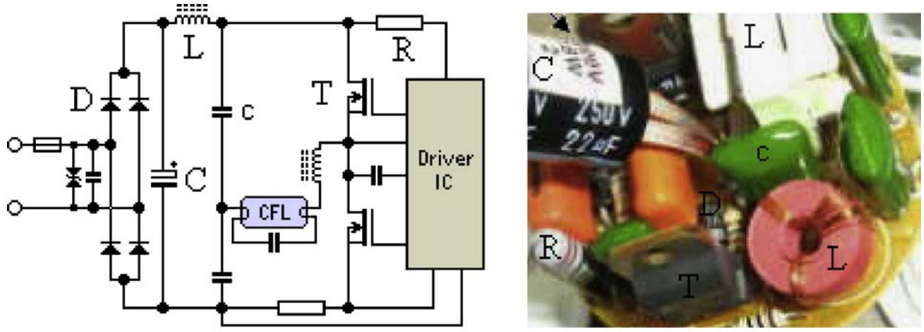
Detrimental affects of a few customers may be overlooked but huge power losses arising out of widespread adoption of CFL cannot be ignored. CFL current with no or poor, average and excellent filtering may be in range of 180–200, 100–130 and 5–10% [4]. It is difficult to allay CFL induced harmonics due to their dispersed nature. It is easier to design high power factor and low THD compact fluorescent lamps by employing in-built filters compared to utility level mitigation. Passive or active power factor correction circuits may cost \$0.50–0.85 or \$2.0–2.50 per CFL [5]. If CFL load is as high as 26% of building's load then voltage THD would remain below 5%. Simulation results show a typical building may have 115% current THD at power factor of 0.60. Some researchers found few CFL having capacitive PF of 0.55–0.93. However, electric power loss in a typical office building wiring due to current harmonics may be more than twice of the linear loads due to higher resistances. Capacity of a transformer may decrease down to 50% in the presence of harmonics due to eddy current losses. Rated 220 V AC is not enough to start the fluorescent lamp that requires an electronic ballast to provide the starting 600–1000 high voltage ignition spike. CFL produces odd harmonics.

Four CFL simulation study showed 28.5% current THD, 0.92 PF, wiring and iron core hysteresis losses due to eddy currents [6]. Low PF and high current THD CFL squanders power rather than conserving energy. There are many technologies to correct power factor and mitigate harmonics. Methods of PF and THD mitigation using active PF correction and a harmonic filter circuits already reported by many researchers [7–8]. CFL not only produces harmonics rather its own performance is seriously affected in the presence of high voltage THD. It is a positive feedback effect that in case of wide adoption of CFL technology may lead to run way. Arseneau and Quellette [2] studied adverse effects of voltage harmonic distortions on performance of CFL. They reported variations in power factors and current harmonic distortion under voltage harmonics rich power supplies. Similar magnetic ballast CFLs power factors at THD_V 0.1% mains power supply may vary from 0.50 to 0.53 and THD_I from 9.2 to 12.8%. Electronic ballasts PF varies from 0.55 to 0.58 but their THD_I increases to 78.70 to 82.90%. Even the most expensive 0.97–0.99 high PF CFL was found to have 12.5–20.9% THD_I. It is worth noting PF of multiple make magnetic ballast CFLs at 4.6, 15.5 and 36.4% mains power supply THD_V may vary from 0.46–0.53, 0.43–0.53 to 0.46–0.55 whilst theirs THD_I varies from 9.0–12.8, 8.6–12.9 to 13.2–16.8%, respectively. However, electronic ballast CFL PF may vary from 0.54–0.59, 0.33–0.35 to 0.42–0.37 and THD_I from 84.3–87.8%, 94.4–99.5% to 92.8–99.8%, respectively. Even for supply with $THD_V < 2.5\%$ the THD_I varies from 92.3 to 143.9%. Attenuation factors for 3rd to 7th harmonics decrease with increasing wire length but start increasing with wire length for 9th harmonic [1].

CFL cannot operate in microwave ovens, refrigerators, humid indoor or out door locations. CFL operation exhibits optimum performance at 20 °C and its efficiency decreases at higher and lower temperatures. At extremely low temperatures the CFL may fail to start without cold start circuits which again increase cost reducing power saving. According to a Chinese researcher [9] their CFL technology is 40% less efficient than competitive Western technology. Chinese produced 3.0 billion CFL in 2007 that is about 80% of world CFL market. Quality check passing rate is 100% for large manufacturers, 62.5% for medium and 50% for small companies. Chinese consume 1 billion CFL in homeland exporting the rest abroad. It is not sure what will be the fate of surplus 200 millions defective CFL pieces? Strict health compliance laws do not allow manufacturing CFL in Europe and USA. Many companies have chosen China and India due to their relaxed public health laws. Five to six foreign companies in addition to many local companies make CFL in China a few in India. Chinese exponentially rising CFL production is shown in Fig. 2.

China seems to phase out conventional bulb production by 2010 when CFL production would exceed 5 billions per year. In 2002 about 80% of world CFL production came from China [10]. CFL production is likely to decline by 2015 due to CFL's long life. Chinese Government distributed 29 million CFL, 21 million linear and some LED lamps in 2008 [11]. May be WAPDA buys 30 million CFL worth Rs6.7 billion in 2010.

New CFL glass prevents UV escape but aged pieces may not stop leakage completely. CFL phosphors are gradually sputtered off due to bombardment of electrons. Some types of CFL have been found to emit UV-B and traces of UV-C radiations [12]. NEMA rules force manufactures to use maximally 5 mg of mercury for CFL < 25 W and 6 mg for 25–40 W CFL. Glass walls and tube electrodes gradually absorb mercury. When mercury runs out the CFL starts glowing dim pink. CFL manufacturers claim (@0.012 mg Hg/kWh)



(a) CFL drive circuit (b) Drive circuit picture

Fig. 1. Compact fluorescence lamp ballast [3].

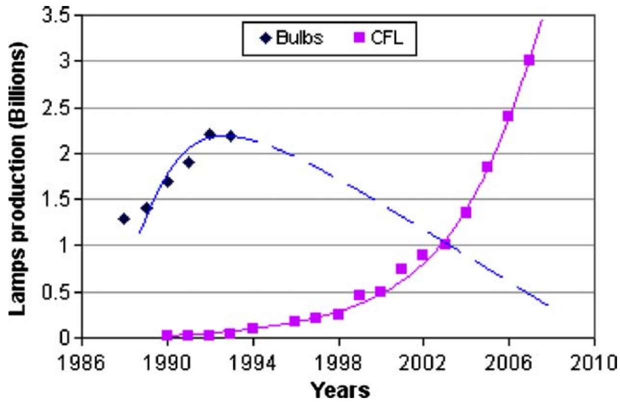


Fig. 2. Chinese bulb and CFL production rates [data from Refs. [9,10]].

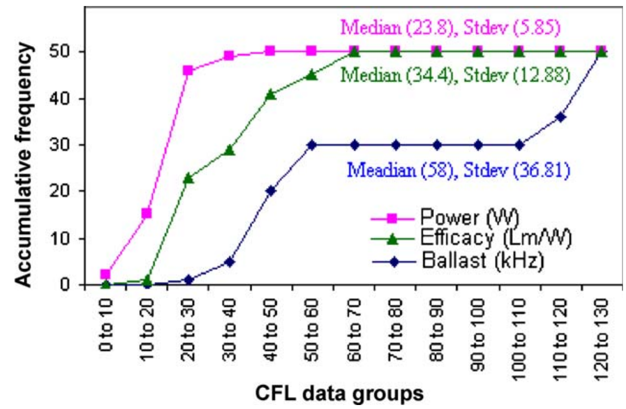


Fig. 3. Multiple vendors CFL powers, ballasts and efficacies.

CFL emits 1.8 mg of Hg compared to 5.8 mg of Hg emission from power plants for using incandescent lamps. It is fair to add LED lamps emit even half compared to CFL. Anyway, a normal thermometer contains 1500 mg Hg that is 300 times worse than the worst quality CFL. Fish containing Hg, Vegetable and Fruits containing pesticides are much more dangerous than using CFL. If 65 CFLs are shattered then Hg level exceeds 100 times the recommended safe-limit which is important for workers disposing off CFL. Many young healthy laborers die young as a result of earth filled evils. Fluorescent lamps using magnetic ballast produce flicker in luminous flux at twice of mains frequency. Flicker induced stroboscopic effect may cause a rotating fan look as if stationary. CFL flickering deficiency may be overcome using lead lag circuits in magnetic ballasts or employing electronic ballasts. However, CFL emits electric and magnetic fields in high frequency range (30–60 kHz) that may interfere with radio and remote control as written on CFL's own lamp box. However, EEFL operating at 0.23–210 kHz frequencies have high luminous efflux and long life. ELFL or radio-fluorescent lamps (RFL) have high PF > 0.9 and low current THD ≤ 2–3%. CFL data analysis shows a median power of 23.8 W with standard deviation of 5.85, a median ballast frequency of 58 kHz with standard deviation of 36.81 and a median efficacy of 34.4 Lm/W with standard deviation of 12.88. Cumulative frequency plot of CFLs powers, ballast frequencies and efficacies of random 50 samples of multiple companies is shown in Fig. 3.

LEDs and electrode less induction lamps have 9–10 times longer lives compared to CFL. They have higher PF and lower THD compared to CFL. LED lamps use RGB system or multiple phosphors technique to produce white light. Electrical control of photon diffusion is complex phenomenon so commercial white light LEDs are made of phosphor. An InGaN, ZnSe, or SiC blue or UV LED excites phosphors to produce white light. Superluminescent LED (SLED) has much higher efficiency compared to conventional LED. White light LED spectrum spreads over 500–700 nm centered at 550 nm. Incandescent lamp spectrum spreads over 400–850 nm centered over 600 nm whereas sunlight spreads from 400 to 7500 nm centered at 530 nm. Organic LEDs (OLED) called polymer LED (PLED) or flexible LED (FLED) have relatively lower life and efficiency compared to crystalline LEDs. A typical high power LED (HPLED) requires a few hundred mA to 1 A current. CFL consumes 3.5 times lesser electricity than incandescent lamp but LED consumes 7–10 times lower than bulbs and 2–3 times than CFL.

Replacement of 110 million people's one 60 W bulb by a 15 W CFL saves energy equivalent to removing 1.3 million cars off the road then option of 9 W LED lamp saves more than twice. CFL lamps prices vary from $5 (open market) to $19 (Walmart) in USA. However, Chinese Phillips CFLs are available for $0.5 to $2 in Pakistan. A typical LED lamp costs $50–160 in USA [13] but same is available for just $4–5 in Pakistan. Here comes quality to which public is not aware. Three rooms lit for 50,000 h with 1 LED, 5 CFL and 42 incandescent lamps will pay bills of $95.95, $159.75 and $652.50, respectively. All lamps except LED use mercury that is a major health threat [14]. Cold cathode fluorescent lamp (CCFL) technology is limited to nixie tubes and neon signage but EEFL supersedes all lamps due to its 100,000 h life. Magnetic blast fluorescent lamps produce 120–180% current THD at 0.40–0.60 PF but electronics blast LED and CFL produce typically 20–30% current THD at 0.8–0.9 PF but certainly will cost more. LED turns on instantly compared to delayed full brightness of CFL. LED lamp emits only 3 btu compared to 30 btu by CFL and 85 btu by bulb in 1 h operation. We have to decide ourselves to choose among the economic (CFL), more economic (tube) and most economic (LED) lamps.

2. Technical analysis

Lamp cost depends on its rated power, current THD, PF, life, efficiency, efficacy, CRI and environmental effects. Two lamps of same rated power (10 W), 82 CRI, 2700 CCT, 520 lumens output may cost $9–10 for 8000 h life, high current THD and low PF or $40–50 for 12,000 h life, low current THD and high power factor. No doubt, CFL and LED lamps save energy but the energy conservation factors projected by the manufacturers are often overstated. CFL starting inrush current is 20–100 times higher than the steady state current. A 20 CFL 200 W festoon draws an average current of about 1.6 A but a peak current of 116 A. CFL operating at 0.50 PF may require 2 times larger apparent power for which utility needs to maintain twice generation capacity. Normal customer looks economy cost lamps without bothering about THD and PF. Wide spread CFL adoption is causing utilities heavy energy losses. Utilities might start thinking to introduce low PF and high THD penalties to recover their losses. Bulbs are cheaper but their efficacies and efficiencies are much poorer than CFL, fluorescent tubes and LED lamps. Tube, CFL, LED and EEFL power requirements are 4.35–5 times lower than bulbs for the same luminous flux. A 100 W bulb produces same luminous flux as 18 W fluorescent tube, 23 W CFL, 15 W LED or 21 W EEFL lamp as shown in Table 1.

Bulb life (1000 h) is much shorter than tube (5000 h), CFL (10,000 h), LED (50,000 h) and EEFL (100,000 h). Bulb @10 h/day use can ideally run for 3 months 10 days, tube for 1 year 4 months 20 days, CFL for 2 years 9 months 10 days, LED lamp for 13 years 10 months 20 days and EEFL for 27 years 4 months and 8 days. A solar dish or skylight domes and PV systems have 30 and 35 years life (@10 h/day). Fiber optic solar dish, skylight domes and PV systems cost $5500–10,000, $127–483 and $2900 per unit, respectively. All

Table 1
Comparison of normal bulbs compared to other lighting lamps.

Lamps (types)	Power (W)	Operating frequency	Efficiency (%)	Efficacy (Lm/W)	Formula (W × Lm/W)	Output (Lumens)
Bulb	100	50/60 Hz	1.9–2.6	17 (12–20)	100 × 17	1700
Tube	18	50/60 Hz	9–15	94 (70–100)	18 × 94	1692
CFL	23	30–100 kHz	8–11	74 (50–80)	23 × 74	1702
LED[a]	15	DC	20–22	113 (80–150)	15 × 113	1700
EEFL	21	2.5–3 MHz	9–14	81 (80–82)	26 × 65	1701
Ideal source	7	CW	35–37	242	7 × 242	1700
Theoretical limit	2.5	CW	100	683	2.5 × 683	1700

[a] LED efficacy 100 (available), SLED 130 (demonstrated) and 180 (realized).

Table 2
Twenty-three years costs analysis of lighting lamps (USA-$).

Parameters	Dish	PV	Bulb	CFL	LED	Tube	EEFL
Lamp power for 1700 lm	Fixed one mini	Fixed 4 Panel	100	23	15	18	21
Lamp life (thousands hours)	solar dish[a] costs $10^4	$300 × 4 42 DC	1	10	50	20	100
kWh (units) used in 100 kHr		Battery $50 × 28	10,000	2300	1500	1800	2100
Energy cost ($) @6/kWh		control $50 × 6	600	138	90	108	126
Retail lamp price/unit ($)			1	11	50	16	60
Lamps used in 100,000 h			100	10	2	5	1
Lamps costs ($) in 23 years			100	110	100	80	60
Total costs ($) in 23 years	3500	2900	700	248	190	188	186
Avg. lighting cost ($/h)	3.19	2.64	0.7000	0.248	0.190	0.188	0.186
Most economic choice	7th	6th	5th	4th	3rd	2nd	1st

[a]200 lumens per module.

Table 3
Twenty-three years costs analysis of lighting lamps (Pakistan-Rs).

Parameters	PV	Dish	Bulb	EEFL	CFL	Tube	LED
Lamp power for 1700 lm	4 Panel Rs60 K 42 DC	Fixed one mini solar	100	21	23	18	15
kWh (units) used in 100 kHr	Battery 112 K control Rs50 K	dish costs $10^4	10,000	2100	2300	1800	1500
Energy cost (Rs) @6/kWh			60,000	12,600	13,800	10,800	9000
Retail lamp price/unit (Rs)			20	3600	170	400	347
Lamp life (thousands hours)			1	100	10	20	50
Lamps used in 100,000 h			100	1	10	5	2
Lamps costs (Rs) in 23 years			2000	3600	1700	800	794
Total costs (Rs) in 23 years	222,000	210,000	62,000	16,200	15,500	11,600	9694
Avg. lighting cost (Rs/h)	2.02	1.91	0.620	0.162	0.155	0.116	0.096
Most economic choice	7th	6th	5th	4th	3rd	2nd	1st

inclusive per hour lighting costs using bulbs, tubes, CFL, LED, solar dish and PV systems are shown in Table 2.

EEFL is cheapest on long term basis in western countries where people do not mind spending buying expensive lamps giving long term economy. However, CFL is 1.31, 1.32 and 1.33 times more expensive than LED, tube and EEFL lamps, respectively. CFL appears 2.82 times cheaper than bulb but if the reactive power loss is considered then CFL is hardly 50% cheaper than conventional incandescent bulbs. Anyway, ELFL lamps are much more expensive

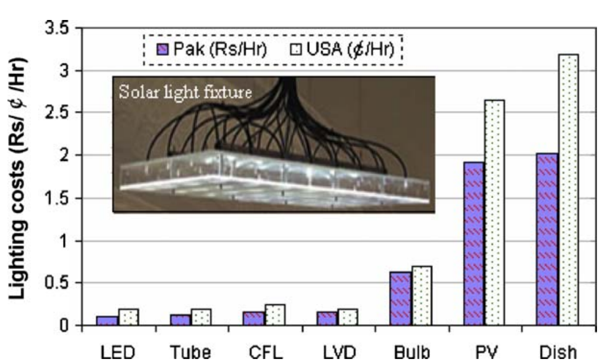


Fig. 4. Per hour lighting costs in Pakistan and USA [solar fixture from Ref. [15]].

compared to CFL and LED lamps so people from power crises hit countries cannot afford to buy. Asian manufacturers, purportedly Chinese, can deliver goods at lower prices due to lower labor costs with compromised quality. Generally, electric goods cost 3–7 times lesser in Pakistan compared to USA. One hour lighting costs including lamps and energy costs in Pakistan are shown in Table 3.

Per hour lighting cost using fiber optic dish is cheaper than PV in USA and other way around in Pakistan. Similarly, EEFL is best option in USA but LED in Pakistan. However, fluorescent tube remains second option worldwide. Energy consumption and investment analysis shows CFL comes at 4th position in USA and 3rd position in Pakistan. Comparison of per hour lighting costs in Pakistan (@electricity cost Rs6/kWh) and USA (@electricity cost ¢6/kWh) using different options are shown in Fig. 4.

Salaries rates are 10–20 times lower in Pakistan than USA but the commodities are only 2.90–3.0 times cheaper. American skilled manpower avails 3.44–6.7 time more benefits than similarly skilled manpower in Pakistan. General workers earn 15–20 times worse than similar workers in most western countries including USA. Lack of jobs, education and health facilities is manifesting itself as basis of revolutionary political changes.

A 15 W CFL weighs 98 g compared to 31 g 100 W bulb that costs more to distribute CFL over longer distances using fossil fuels run vehicles. It takes 1 kWh to manufacture an incandescent lamp

Table 4
Technical characteristics of bulb, tube, CFL and LED [16].

Lamps	Sizes (W)	THD_I	PF	P_{loss} (W)	CCT (K)	BE[a]	Glare	CRI[b]
Bulbs	25–1000	0%	1	0%	2500–3000	No	Yes	90–99
Tube	20–40	10–180%	0.6–0.8	12.50%	2500–6500	Yes	Yes	55–70
CFL	8–36	10–180%	0.4–0.6	6.25%	2500–6500	Yes	Yes	55–75
LED	5–400	10–180%	0.4–0.7	4.25%	3500–5500	No	Yes	70–80
EEFL	15–400	2.7%	0.98	15.10%	2500–6500	Yes	No	>80

[a] BE = bio-effects.
[b] Sunlight color rendering index (CRI) = 100.

Table 5
Quality factors of light lamps.

Parameters	LED	EEFL	Tube	Bulb	CFL
Price factor (+A_a)	+0.01	+0.00	+0.07	+1.00	+0.14
Bill factor (+B_a)	+1.00	+0.55	+0.77	+0.14	+0.58
CRI factor (+C_a)	+0.75	+0.81	+0.65	+0.90	+0.65
Efficiency (+D_a)	+1.00	+0.64	+0.64	+0.09	+0.45
Efficacy (+E_a)	+1.00	+0.72	+0.83	+0.15	+0.66
Long life (+F_a)	+0.50	+1.00	+0.20	+0.01	+0.10
Glare factor (+G_a)	+0.00	+1.00	+0.00	+0.00	+0.00
Health factor (+H_a)	+0.80	+0.50	+0.50	+0.90	+0.50
Power factor (+I_a)	+0.60	+0.98	+0.60	+1.00	+0.60
THD factor (+J_a)	+0.20	+1.00	+0.20	+1.00	+0.20
Spare factor (+K_a)	+0.30	+0.50	+1.00	+0.00	+0.10
Pollution factor (+L_a)	+0.90	+0.40	+0.30	+0.90	+0.40
Green factor (M_m)	+1.00	+0.75	+0.64	+0.15	+0.49
Σ (Factors sums)	7.91	7.85	6.37	6.24	4.87
Quality: $\bar{Q}$ (%)	60.84	60.38	49	48	37.46

whilst it takes 4 kWh for a CFL. CFL may go bang at night or day in chemical industries adding fire risk. A broken CFL emits 5–6 mg mercury in air. A typical CFL circuit has six diodes, 5 capacitors, 2 transistors, 2 inductors, 2 resistors, 1 fuse and 1 drive IC in ballast circuit. High THD, low PF, energy wastage and bio-effects render CFL as the last option compared to alternative light sources. Typical characteristics of bulbs compared to fluorescent tubes, CFL and LED lamps are shown in Table 4.

Light lamp may be characterized by the energy consumption, price, THD, PF, output luminous flux, efficacy, efficiency and CRI. Tubes, CFL and LED lamps can satisfy quality requirements if their current THD < 10–20% and PF > 0.90. Transparent 60, 75, 100 and 200 W incandescent lamps radiate 660–1100, 874–1100, 1246–1700 and 2000–2600 lumens light, respectively. High THD and low PF 23 W CFL or 20 W tube emit 15,000 lumens. Change of LED output luminous flux as function of input power compared to incandescent, compact fluorescent and halogen lamps is shown in Fig. 5 [90% data from Ref. [17]].

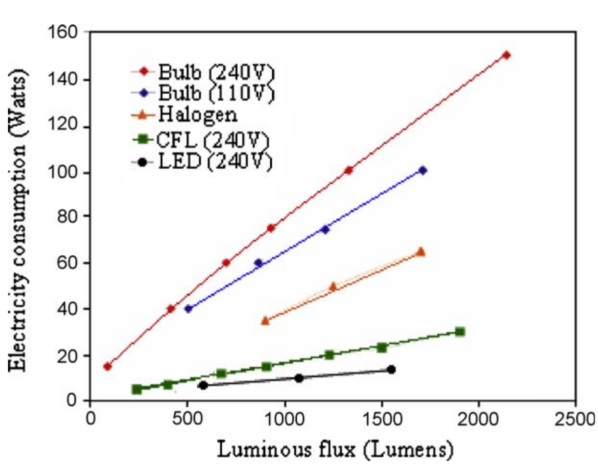


Fig. 5. LED luminous flux as function of rated power [17].

Normal 13, 30, 100, 160 and 200 W LED lamps give off 1200, 2400, 8000, 12,800 and 16,000 lumens, respectively. Incandescent bulbs have low THD and high PF but they waste lot of power due to poor 1–2% efficiency. Different lamps come with various characteristics which may be integrated into a quality factor for ultimate comparison. A quality factor may be defined in terms of equal weights of lamp life, efficiencies, efficacies, prices, THD, PF, spares, power quality, environmental and biological effects. To optimize the suitable lamp choice a quality factor is being introduced as follows:

$$Q(\%) = \frac{A_a + B_a + C_a + D_a + E_a + F_a + G_a + H_a + I_a + J_a + K_a + L_a + M_a}{A_m + B_m + C_m + D_m + E_m + F_m + G_m + H_m + I_m + J_m + K_m + L_m + M_m} \times 100$$

Subscript "a" refers to actual values and subscript "m" refers to possible maximum values. Quality parameters values for bulb, tube, CFL, LED and EEFL were normalized by the best parameter to assign fractional weights as shown in Table 5.

Different quality parameters ranging from 0 to 1 were decided as follows:

A_{actual} = 23/lamp price (Normalized to lowest cost of incandescent lamp i.e. Rs23).
B_{actual} = 0.096/all inclusive Rs per hour costs (normalized to lowest LED rate 0.096/h).
C_{actual} = CRI/99 (normalized by LED color rendering index (CRI))
D_{actual} = efficiency/22 (normalized by LED's 22% efficiency)
E_{actual} = 113/lamp efficacy (normalized to LED's efficacy)
F_{actual} = lamp life (h)/100,000 (normalized to electrode less inductive LVD life)
G_{actual} = 0 (with glare) and 1 (without glare)
H_{actual} = 0.5 (Hg and bio-effects), 0.2–0.4 (Hg or bio-effects, HV) and 1 (none).
I_{actual} = as per actual power factor lowest range number.
J_{actual} = 1 for low THD, 0.2–0.3 for >78% THD > 32% > 78%, 0 for THD > 78% (IEC Std)
K_{actual} = 1 for spare parts facility, 0.2–0.3 for chance, and 0 for complete replacement.
L_{actual} = 1 for environmentally safe, 0.1–0.2 for IR/UV and 0 for soft X-ray emission.
M_{actual} = green factor (LED lowest power divided by equivalent other lamps powers)

Above quality criterion is the first move and open for criticism. Quality analysis rates electric light lamps as LED (outstanding), EEFL (excellent), fluorescent tube (good), incandescent lamp (acceptable) and CFL (bad).

Relative quality factors of LED, EEFL, tubes, bulbs and CFL lamps depending upon their cost, lamp life, efficacy, efficiency, THD, PF, repair, glare, energy consumption, pollution and bio-effects are shown in Fig. 6.

According to timeline of lighting technologies human race discovered wood (5500 BCE), oil lamps (4500 BCE), candles

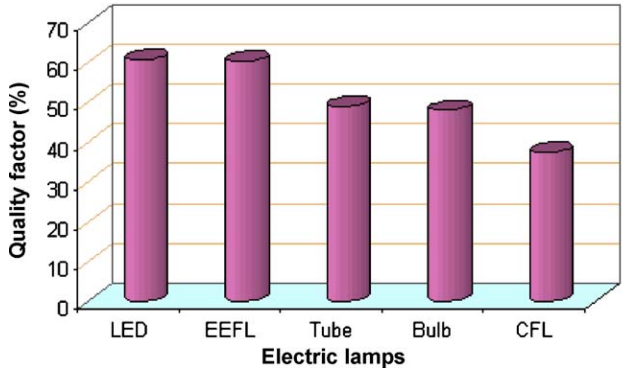


Fig. 6. Weighted electric lamps quality factors.

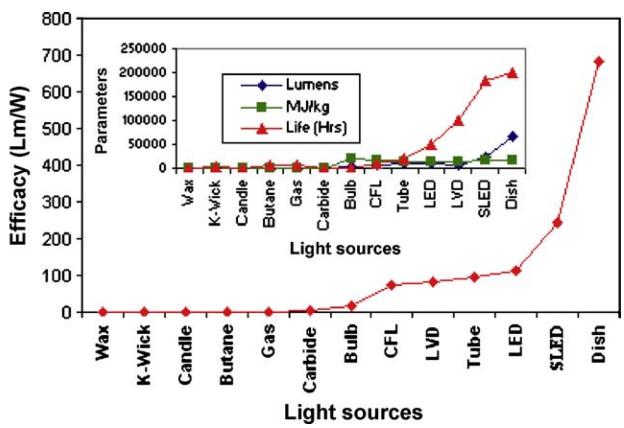


Fig. 7. Lighting sources characteristics.

(3000 BCE), kerosene oil wick (900 CE), open gas lighting (1792), open air electric arc lamp (1802), incandescent bulb (1880), incandescent gas mantle (1889), tungsten filament bulb (1998), mercury vapor lamp (1900), fluorescent lamp (1925), LED (1960), CFL (1972), OLED (1987), EEFL (1991) and sulfur lamp (1994) in last 7500 years since dawn of mankind. Human being enjoyed sunlight and heat since antiquity and will continue to have it when every fuel depletes on planet earth. We are slowly heading towards post-carbon era. Today we have a huge variety of lamps but power and energy crisis has hit the homes. Wood, wax, carbide mantle and candle light sources have only few lumens efficacy. Lighting sources efficacies, luminous efflux, energy per kg fuel and life spans are shown in Fig. 7.

Optical scientists and engineers have developed truncated pyramid concentrators, parabolic dishes, tubular skylight roof domes and white light optical fibers to collect sunlight to deliver it to large buildings dark interiors [18]. Several companies have introduced natural light lamps to conserve daytime lighting energy. Canadian Sunlight Direct full spectrum hybrid solar lighting dish (Model HSL 3000), Natural Sky Lighting tubular roof dome (TSL-900) and Japanese Himawari lenses arrays can adequately illuminate large dark buildings at least daytime. Solar fixture [15] shown in Fig. 4 is used with solar dish or similar fiber distributed lighting systems. Ceiling mounted solar collector or dish can illuminate 1000 ft^2 area rooms up to 15 m away. Himawari collector can serve up to 33 interior fixtures.

Recent studies have focussed on various aspects of harvesting free solar energy for lighting, heating, drying and electricity production applications. Schlegel et al. [19] analyzed economic use of full spectrum hybrid lighting, Wu et al. [20] engineered solar powered LED roadways lighting systems, Marium et al. [21] reviewed impact of daylight saving time (DST) on saving electric lighting energy, Kaiyan et al. [22] developed efficient solar light concentrator for fiber optic take away and Ghisi et al. [23] evaluated potential for energy saving out of fiber optic solar lighting of largely populated complexes. Huang et al. [24] developed high performance photovoltaic based LED lighting systems. Hybrid solar systems use IR and white light filtering mirrors to produce electricity from thermal photovoltaic (TVP) and illuminate building interiors through fiber optics. Fused silica windows may be used if optical fibers melt. Lighting energy saving may range from 8 to 90% in different countries. There is a general feel the LED lamps are not getting wide spread acceptance among users. May be it is due to directional light that urgently need to be corrected using diffusers [25]. Pode [26] has pointed out recently a solution how to increase the acceptability of LED lighting technology. Globally noted barriers may include lack of awareness of business community, lack of media campaign, limited technical skill, high cost and lack of international policy to promote LED lights. Efficacy comparisons of LED with conventional incandescent bulbs and CFL technology are shown in Fig. 8.

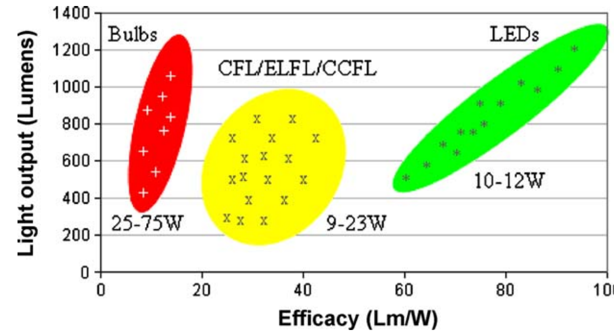


Fig. 8. Efficacies of common residential lamps in market.

3. Market analysis

Government energy conservation agencies and utilities generally prefer CFLs over incandescent lamps. Planning Commission, Government of Pakistan approved Rs6.7 billion to purchase 30 million CFLs through PEPCO to conserve worth Rs17 billions energy. It costs Rs223.33 per CFL whereas CFLs available in market cost Rs50 (Chinese) to 170 (Phillips) per CFL. Energy analysts and anchors complain the government is paying Rs53–173 more than market price at the cost of national exchequer. The cost could be brought down to Rs2.5–3 billions by negotiation. Enercon's MD suggested LED lamps instead of CFL and UN energy consultant called it wastage of public money [27]. Some experts prefer electrode less induction based EEFL (LVD) lamps whilst Enercon recommended LED lamps. Chairman's remarks on specific quality could mean something if incumbent authority quantifies PF and THD of proposed energy savers. CFL cost ultimately depends on the type of circuits used in CFL. Generally CFL cost may vary from $0.50 to $50 depending upon its PF and THD. Power quality engineers have noted serious implications of excessive use of CFL on power distribution system. CFL generates harmonics in power system and operate at lower power factor. CFL not only distorts utility sinusoidal power supply waveform forcing utilities to supply more apparent power than real load, itself is also affected by the presence of harmonics. Variation of CFL prices with rated voltage and power compared to LED, tubes and EEFL (LVD) is shown in Fig. 9.

CFL prices vary with wattage and make due to differences in efficiencies. A 8–11, 18, 23 and 24 W Phillips make CFLs cost 145, 150, 170 and 180 rupees, respectively, in Islamabad but Crystal make 18–26 W CFLs cost 150–180 rupees in market. CFL rates are

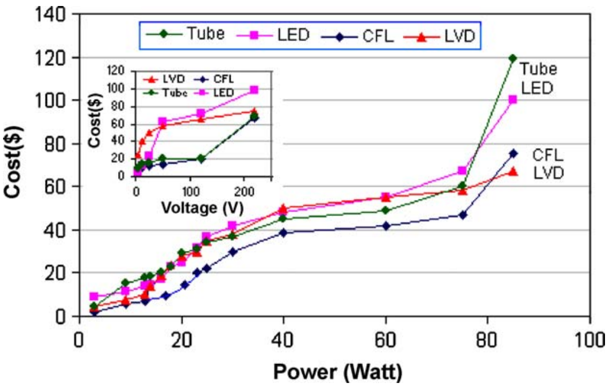


Fig. 9. Variation of lamps prices with rated powers and voltages.

around Rs7–13/W in retail sale in Pakistan. Rates for small size lamps are relatively higher compared to large size CFL lamps. A Chinese make 10 W CFL cost Rs35, therefore, lowering Rs/W rates down to 3.5. A 40 W fluorescent light tube costs Rs400–450 whilst a 5 W LED lamp may cost Rs347–500. Incandescent lamps cost vary from Rs23 (pins) to Rs25 (screws). PEPCO's proposed CFLs cost Rs223.33 each leading to a budget of Rs6.7 billions for 30 million pieces of unknown type, make and rating. If government agencies opt to buy Chinese make cheap 10 watt CFLs then a sum of Rs5.64 billions out of Rs6.7 billions (83.50%) can easily be gashed in purchase of 30 million CFLs. It would force PEPCO to supply 180 million kVA per month for the price of only 90 million kWh due to low power factor and high THD. PEPCO will continue to loose at rate of Rs360 millions per month for at least 2 years 9 months 10 days the rated life of CFL. PEPCO losses will accrue from minimum Rs12.24 billions (for 0.5 PF CFL) to maximum Rs15.30 billions (for 0.4 PF CFL) if they purchase Rs223 per CFL having low PF and high THD. If we add the offset amount of Rs5.64 billions then the overall loss may rise to 17.88–20.94 billions instead of gaining Rs17 billion energy conservation benefits. Overall costs in USA are 2–4 times higher than Pakistan but this factor is negligible compared to 13–20 times lower income rates. It means people living in Pakistan are naturally 5–7 times less rewarded compared to developed nations. PEPCO may suffer more energy losses if wrong type of CFL is purchased for widespread subsidized or free distribution. Government drive to finish Rs55 billions subsidy on electricity is an unwelcome decision as it can further worsen the power crisis. Pakistan needs to expend more efforts to curb corruption rather than wasting resources on imported oil fired rental power plants and free low PF CFL distribution project [28]. PEPCO claimed (and actual) consumer savings using four 100 W bulbs, 40 W tubes and 20 W CFL are shown in Table 6.

Most touted LED and CFL power consumptions of 10 and 20% of incandescent bulbs seem exaggerated, respectively. Average bulb, tube and CFL efficacies are 17(12–20), 94 80–100), 74(50–80) limens per watt. Selecting above average efficacies, a 100 W incandescent bulb, 18 W fluorescent tube and 23 W CFL can produce equally 1700 lumens light flux. We can correct to revise Table 6 by replace 40 W by 18 W for tube and 20 W CFL by 23 W for CFL as shown in Table 7.

Considering average quality CFL and tubes with 0.70 PF, the amount of energy (kWh) consumed in a month at rate of 3.5 h daily lighting, the utility losses would increase and overall consumer saving might also be affected. Electronic ballasts operate at 500–600 times higher frequencies compared to magnetic ballasts. Electronic ballast efficiency starts improving from 10 to 20 kHz operation. 75% of the magnetic ballasts in 1988 were PF corrected and 24% uncorrected whilst only 1% were electronic type. Almost 41% magnetic ballasts were PF corrected and 21 uncorrected whilst 38% were electronics type. Today mostly electronic ballasts are used with CFL but still old uncorrected magnetic ballasts are used with tubes [29,30]. Every home has 50% of electronic and magnetic ballasts whose power losses are in range of 5–25 and 20–54%, respectively. Electronic ballasts consume 20–25% less power than magnetic ballasts [31]. Furthermore, operation of CFL at 110 V and 60 Hz is more efficient than 220 V 50 Hz. However, efficiency of SiC devices at high voltage compared to lower voltage operation. Examination of T8 and T5 type fluorescent lamps shows a 36 W T8 lamp using magnetic ballast consumes 46 W power whereas electronic ballast lamps consumes only 37 W. Despite correction the THD of magnetic and electronic ballasts remain 11 and 6% increasing lamp efficacy from 64 to 80 lm/W [32]. Electronic ballast is operated at 50–52 kHz to avoid interference with remote control at 40 kHz.

It is quite reasonable to assume tube magnetic ballast losses 21.74% and CFL electronic ballast losses just 8%. Modern CFL claim ballasts claim to have 6.25% losses but EEFL losses still around 15.10%. A few years older brand 18 W tube wastes 5 W in magnetic ballast (choke) and 23 W CFL just 1–2 W in its electronic ballast [33]. Independent studies have reported magnetic ballast lamps sold as 9 W to measure from 11.05 to 16.47 W (+2 to +7.47 variance) whereas electronic ballasts lamps sold a 11 W to measure from 10.82 to 13.02 W (−0.48 to +2.02 variance) [34]. Consumer monthly consumptions for bulb, tube and CFL at rate of 3.5-h/day use of lamps, ignoring voltage and current harmonics effects but including ballast losses, are shown in Table 8.

Table 6
Perceived monthly savings for 4 lamps @3.5 h daily use.

Lamp	Power	Load	Consumption (kWh)		Public saving (%)	
Types	(W)	(W)	Claimed	Actual	Claimed	Actual
Bulb	4 × 100	400	42	42	–	–
Tube	4 × 40	160	18	16.8	57%	60%
CFL	4 × 20	80	9	8.4	80%	80%

Table 7
Corrected actual monthly savings for 4 lamps @3.5 h daily use.

Lamp	Power	Load	Consumption (kWh)		Public saving (%)		Utility
Types	(W)	(W)	Claimed	Actual	Claimed	Actual	(losses)
Bulb	4 × 100	400	42	42	00%	00%	00%
Tube	4 × 18	72	18	7.56	57%	82%	18%
CFL	4 × 23	92	9	9.66	80%	77%	33%

Table 8
Monthly energy consumption considering ballasts power losses.

Lamp (type)	Power (W)	Load (W)	Units (kWh)	Public saving	Utility (kVArh)	Tariff (kVAh)	Utility (Loss)
Bulb	4 × 100	400	42	00%	00	42	00.50%
Tube	4 × (18 + 5)	92	9.66	77%	9.85	13.80	30.00%
CFL	4 × (23 + 2)	100	10.50	75%	10.71	15.00	30.00%

Table 9
Monthly energy consumption considering effects of harmonics.

Lamp (type)	Power (W)	Load (W)	Units (kWh)	Public saving	Utility (kVArh)	Tariff (kVAh)	Utility (Loss)
Bulb	4 × 100	400	42	00%	00.00	42	01.00%
Tube	4 × (18 + 5)	92	9.66	77%	14.66	17.56	44.99%
CFL	4 × (23 + 2)	100	10.50	75%	15.95	19.10	45.03%

Considering of ballast losses may reduce customers saving from 82% (tube) and 77% (CFL) down to 77% (tube) and 75% (CFL). Real power systems have voltage as well as current harmonics which further worsen the fundamental power factor. Considering voltage and current THD effects the overall true power factor may be given by

$$PF_{true} = \frac{P_{avg}}{V_{RMS} I_{RMS} \sqrt{1 + THD_V^2(\%)} \sqrt{1 + THD_I^2(\%)}} \quad (1)$$

$$PF_{true} = \frac{PF_{fund}}{\sqrt{1 + THD_V^2(\%)} \sqrt{1 + THD_I^2(\%)}} \quad (2)$$

$$PF_{true} = PF_{fund} \times PF_{Dist} \quad (3)$$

$$PF_{Dist} = PF_{Dist}^{V} \times PF_{Dist}^{I} \quad (4)$$

Decrease in fundamental power factor (viz. PF = 0.70) with fixed 3 and 5% voltage THD and varying current harmonic distortions is shown in Fig. 10.

For 3% voltage and 78% current THD the fundamental 0.70 PF decreases to

$$PF_{true} = \frac{0.70}{\sqrt{1 + 0.03^2} \sqrt{1 + 0.78^2}} = 0.55$$

When current THD is 80–100% the voltage THD is often less than 4%. Usually, current THD remains dominant over voltage THD in actual power systems. However, as a rule both voltage and current THD keep on varying dynamically at different rates. THD may also affect the performance of incandescent bulbs as well as energy meters due to obvious wave shape changes. Generally, voltage THD varies at slower rate compared to current THD. True PF depends both on voltage as well as current THD therefore above calculations are revised for the 0.55 PF_{true} as shown in Table 9.

Compact fluorescent lamps save about 75% energy at expense of 45% utility losses. Compared to CFL equivalent tubes save 77% energy at expense of similar utility reactive power based losses. Fluorescent lamp technology in general and CFL in particular has helped utilities overcome peak shaving and consumers saving. Being energy conservative enthusiasts we can further save more energy using LED lamps. Best way to increase energy efficiency is to pressurize CFL manufacturers to improve PF and current THD to improve overall lighting economy. Use of PV powered lights on remote highways saves lot of money that can be expended on improvement of CFL technology. When we consider ballast losses, voltage and current harmonics the utility reactive power losses further increase as shown in Fig. 11.

4. Power factor (PF)

Lagging PF loads are a nuisance but leading power factor are welcome due to overall lagging PF system. Utilities often try to maintain system PF from 0.85 to 0.95. Low PF loads require utility increasing apparent power to be able to supply small real power loads. Same rated supply can feed 90–95 kW load at unity PF compared to 50 kW load at 0.5 PF. Term PF reflects efficiency of an electrical power distribution system. Loads that cause poor power factor include induction motors, arc furnaces, machining, stamping, welding, variable speed drives, computers, servers, TV, fluorescent tubes, compact fluorescent lamps. Utility charges industries for poor factor but exempts houses and offices. DeAlmeida [48] pointed out

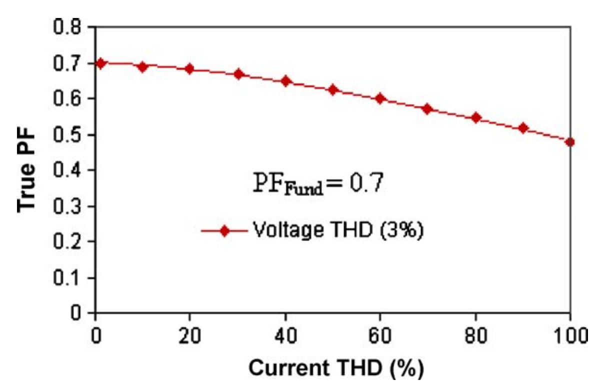


Fig. 10. Variation of true PF with voltage and current harmonics.

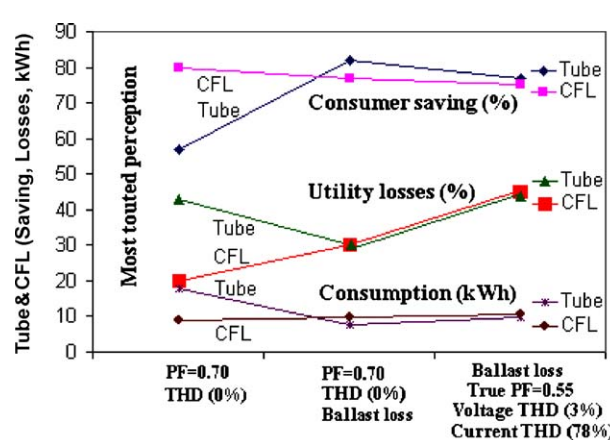


Fig. 11. Impact of PF and THD on utility reactive power losses.

Table 10
Power factor correction capacitor sizing [38].

Original power factors	Corrected power factors										
	0.80	0.82	0.84	0.86	0.88	0.90	0.91	0.92	0.93	0.94	0.95
0.50	0.982	1.034	1.086	1.139	1.192	1.248	1.276	1.306	1.337	1.369	1.403
0.52	0.893	0.945	0.997	1.050	1.103	1.159	1.187	1.217	1.248	1.280	1.314
0.54	0.809	0.861	0.913	0.966	1.019	1.075	1.103	1.133	1.164	1.196	1.230
0.56	0.730	0.782	0.834	0.887	0.940	0.996	1.024	1.054	1.085	1.117	1.151
0.58	0.655	0.707	0.759	0.812	0.865	0.921	0.949	0.979	1.010	1.042	1.076
0.60	0.583	0.635	0.687	0.740	0.793	0.849	0.877	0.907	0.938	0.970	1.004
0.62	0.516	0.568	0.620	0.673	0.726	0.782	0.810	0.840	0.871	0.903	0.937
0.64	0.451	0.503	0.555	0.603	0.661	0.717	0.745	0.775	0.806	0.838	0.872
0.66	0.388	0.440	0.492	0.545	0.598	0.654	0.682	0.712	0.743	0.775	0.809
0.68	0.328	0.380	0.432	0.485	0.538	0.594	0.622	0.652	0.683	0.715	0.749
0.70	0.270	0.322	0.374	0.427	0.480	0.536	0.564	0.594	0.625	0.657	0.691
0.72	0.214	0.266	0.318	0.371	0.424	0.480	0.508	0.538	0.569	0.601	0.635
0.74	0.159	0.211	0.263	0.316	0.369	0.425	0.453	0.483	0.514	0.546	0.580
0.76	0.105	0.157	0.209	0.262	0.315	0.371	0.399	0.429	0.460	0.492	0.526
0.78	0.052	0.104	0.156	0.209	0.262	0.318	0.346	0.376	0.407	0.439	0.473
0.80	0.000	0.052	0.104	0.157	0.210	0.266	0.294	0.324	0.355	0.387	0.421

to correct PF by inserting a capacitor in series with one of the two fluorescent tube rods. The idea may be extended to widespread self-PF correction by modifying CFL ballasts. A CFL may be marked as leading or lagging PF so that people may choose appropriate ± PF pairs for self-PF correction. It is much easier to design CFL ballasts with lead and lag PF factors compared to unity power factors. Additional power factor correcting supercapacitors may also be added to CFL ballast. This idea can be applied to self-harmonics canceling through parallel Δ/Δ and Δ/Y distribution transformers or load combinations producing self-canceling harmonics [34–37].

Facility can reduce electricity costs, increasing kW capacity from the same kVA transformer, improve voltage regulation, reduce cables, transformers and switch gear sizes by improving power factor. A customer with 100 kVA load can light seven hundred 100 W bulbs at 0.7 PF and nine hundred 100 W lamps at 0.9 PF. A customer using 100 kW load at 0.7 PF needs 142 kVA apparent power (wasting 100 kVAr reactive power) but the same load would require only 125 kVA capacity (wasting 75 kVAr) at 0.8 PF. Power factor can be improved from 0.7 to 0.8 or 0.95 just by adding a 25 or 67 kVAr capacitor. A power factor correction capacitor sizing multipliers are shown in Table 10 [38].

To obtain correct size of capacitor choose the number in front of existing and proposed PF and multiply it with kW load. To correct existing 0.70 PF to 0.80, 0.90 or 0.95 multiply 0.270, 0.536 or 0.691 with kW load (say 100 kW as above) to get 27, 54 or 69 kVAr capacitors, respectively. If the rated capacitor does not exist then choose the next higher available rating capacitor. A 10 HP squirrel case induction motor of 3600 RPM requires 3 kVAr capacitor but the same rated HP motor of 600 RPM speed requires 7.5 kVAr capacitor. A 50 HP (3600 RPM) squirrel cage induction motor require 12 kVAr capacitor but the same rating 600 RPM motor may require 24 kVAr capacitor. A 4.8 A, 240 V water pump motor requires 2 kVAr capacitor to correct the PF which it worsens in operation. Capacitors require 1.65–2.5 times rating fuse to protect against rupture. Utilities bill facilities on kVA basis through MI, kW and kVAr meters. A 100 kW load at 0.70 PF requires 142 kVA that cost (@$11/kVA) about $1562. Same 100 kW load at 0.80 PF requires 125 kVA which costs $1375. It gives monthly saving of $187 and annual saving of $2244. If equipment costs $4488 then its pay back period is just 2 years. A capacitor improves PF, reduces power loss as well as kVA demand. LV (440 V) capacitors may be connected permanently on lines but MV (11 kV) capacitors need switch gear to operate.

Household consumer electronics products such as air conditioner (0.37), washing machine (0.25), microwave (0.56), computer (0.26) and printer (0.32–0.46) have very low power factors [36].

Table 11
Power factors of typical household appliances.

Appliances (types)	Power Factor (PF)			
		Active	Passive	Off
Bulbs	1	–	–	–
Tube	0.6–0.85	–	–	–
CFL	0.4–0.60	–	–	–
LED	0.43–0.70	–	–	–
EEFL	0.90–0.98	–	–	–
Television (CRT)	0.62	–	0.33	0.28
Television (LCD)	0.59	–	0.27	0.01
TV (projection)	0.64	–	0.22	0.09
TV/VCR	0.59	–	0.46	0.37
VCR	–	0.49	0.40	–
DVD	–	0.50	0.32	0.26
Integrated stereo	–	0.70	0.59	0.40
Portable stereo	–	0.64	0.54	–
Amplifiers	0.66	–	0.79	0.29
Compact disc	–	0.73	0.57	0.19
Stereo receiver	0.68	–	0.54	0.02
Stereo tape deck	–	0.71	–	0.31
Sound amplifier	–	–	0.64	0.26
Stereo tuner	0.83	–	0.78	0.18
Inductor	Lagging	–	–	–
Capacitor	Leading	–	–	–

Table 12
Harmonics nomenclature.

Harmonic	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	...
Sequence	+	–	0	+	–	0	+	–	0	...
Type	Fund	Even	Odd	Even	Odd	Even	Odd	Even	Odd	...

Except incandescent bulbs, declared undesirable due to lower efficacy, all energy saving lamps require additional power factor correction capacitor circuits. Typical power factors of lighting lamps and household appliances working in active, passive or off standby modes are shown in Table 11.

Power factors of operating household electronic appliances are between 0.60 and 0.80 or lower. Power factors of electronic ballasts are 0.40–0.50 if not corrected by adding additional capacitor circuits.

5. Total harmonic distortion (THD)

IEEE Std.519 (1992) recommends keeping voltage THD $\leq$ 5% and current THD $\leq$ 32% in utility power distribution network <69 kV. ANSI C82.77 (2002) recommends all commercial indoor hard wired ballasts >28 W maintain 0.90 PF with maximum 32% current THD. It requires residential hard wired luminaries below 120 W meet a minimum PF of 0.50 with a maximum of 200% current THD. However, it recommends luminaries ballasts <50 W to maintain 0.50 PF at maximum 32% current THD. CFL takes extremely distorted current peaks injecting current harmonics towards electric grid. Capacitors can improve displacement PF but not the distortion power factor. IEC/TR3 61000-3-6 has included allowable levels for low, medium, high and ultrahigh voltage systems. It allows up to 6% voltage THD for 5th harmonic, 5% for 3rd and 2% for 2nd harmonics in low and medium voltage circuits. Maximum permissible harmonic current per watt is 3.4 mA (for 3rd harmonic) corresponding to current THD of 78.2%. Voltage THD arises from the interaction between distorted load currents and utility system impedance. Harmonic voltages and currents are integral multiples of fundamental frequency. Odd harmonics include positive sequence harmonics (h = 1, 7, 13...), negative sequence harmonics (h = 5, 11, 17...) and zero sequence triplen harmonics (h = 3, 9, 15...). Even harmonics (h = 2, 4, 6...) sub-harmonics and inter-harmonics (h = 87.5, 112.5, etc.) are often rare. Some even harmonics (h = 4, 10, 16...) are positive sequence harmonics whilst others (h = 2, 8, 14...) are negative sequence harmonics. Sometimes sub-harmonics are induced in system causing eye sensitivity and sub-synchronous resonance (SSR) in powerhouse generators. Harmonics sequence is shown in Table 12.

One pulse half wave rectifies produce all types of harmonics (h = 2, 3, 4, 5, 6, 7...), two pulse full wave rectifiers produce odd harmonics (h = 3, 5, 7, 9...), six pulse three phase full wave rectifiers produce selective odd harmonics (for even n: $h = 3n \pm 1$ = 5, 7, 11, 13, 17, 19...) and 12 pulses three phase full wave rectifiers produce higher order odd harmonics (h = 11, 13, 23, 35, 37...). Lower order harmonics are significant because of power losses due to their contribution to power factor reduction and higher order harmonics are important regarding interference and eddy current losses. Three phase loads such as variable speed drives and lifts produce (h = 5, 7, 11, 13, 17, 19...) harmonics and single phase loads produce (for odd n: $h = 2n \pm 1$ = 3, 5, 7, 9, 11...) harmonics. Positive sequence harmonics tend to accelerate but negative harmonics tend to decelerate induction motors. However, zero sequence harmonics flow through star point to earth causing excessive heat and power losses. IEEE 519–1992 recommends to restrict odd harmonics <11 down to 4.0% for $I_{SC}/I_L < 20$ and 7.0% for $20 < I_{SC}/I_L < 50$. However, odd harmonics >35 must remain below 1.4% for $I_{SC}/I_L > 1000$. Even harmonics should not exceed 25% of odd harmonics at PCC. For voltage <69 kV the current THD must remain below 32% and voltage THD $\leq$ 5%.

Zero sequence tripling harmonics can add in phase in neutral earthed conductor. Transformers feeding to industrial loads have high neutral currents despite balanced loads. Harmonics of Y–Y connected transformers can travel from primary to secondary through earthed neutrals. Voltage sag sensitive utilities and arc furnaces use Δ–Δ connected transformers to stop harmonics flow [37]. Protective relays tripping, harmonic overloads, high levels of voltage and current distortions, temperature rise in conductors, motors, cables and generators contribute to reduce quality and the reliability of AC distribution system [38,39]. There are about ten different technologies to control harmonics. These technologies include chokes or line reactors (3% criterion), drive isolation transformers (1:1 ratio and k-factor = 4–50), DC chokes (DC side of rectifiers), 12 pulse converters (reduce 85% harmonics), pulse distribution transformer (reduces 50–80% harmonics), tuned parallel filters (improve PF), broadband series blocking filters (improve PF), 18 pulse converter or differential delta autotransformers (cancel 90% harmonics) and series or parallel active filters inject opposite harmonics to cancel 2–50th harmonics to improve system PF. Commercial facilities may opt neutral current blocking filters (reduce 80% neutral currents and 10–30% RMS phase currents), zigzag transformers or zero sequence traps (block upstream harmonics flow), over sized neutral or k-rated transformer (k13 or k20) to use rated capacities. Many engineers substitute harmonic solutions with PF correcting capacitors to increase system capacity of transformers and cables by reducing kVA requirements. Capacitors improve kW capacity reducing load current resulting in decreased I^2R losses. However, harmonics sometimes may resonate to damage PF correcting capacitors. Reduction of harmonics also improves system PF. To avoid harmonic resonance engineers may employ other methods which improve PF as well as reduce harmonics. These methods include harmonic filters, active filters and series broadband drive filters. Adjustable speed drives may employ reactors, 18-pulse converters, phase shifting transformers and synchronous condensers to improve PF avoiding harmonic resonance [40]. Another method is to change capacitor bank to under or over compensate for required kVA provided it does not cause over voltage. Best choice depends on real situations. If a harmonic solution relieves from PF penalty reducing overall harmonics then it may be regarded as the optimum choice.

6. Low PF and high THD scenario

Current THD and PF are two different phenomena arising out of entirely different situations. One of the impacts of current THD is to increase magnitude of RMS current that (I^2R) increases power system losses. However, a small load with 200% THD cannot affect overall system but a large load with even 100% THD can seriously impact the system. Similarly, a smaller load with 0.4 PF cannot affect the system but a large load with 0.6 PF can adversely impact the system as THD also manifests itself in low PF. Distortion factor (I_F/I_{RMS}) lowers overall power factor. Reducing harmonics or improving power factor reinforces each other but PF cannot be unity in the presence of harmonics. As the PF reflects overall losses, therefore, harmonics contribute to power loss. Harmonics affect displacement factor so the total kVA demand increases. Total

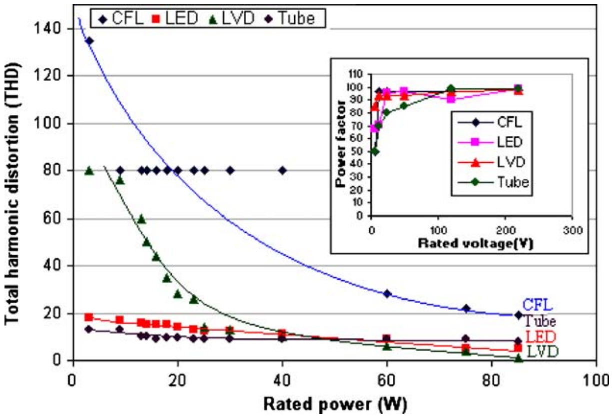


Fig. 12. THD and PF variation with rated lamp power and voltage.

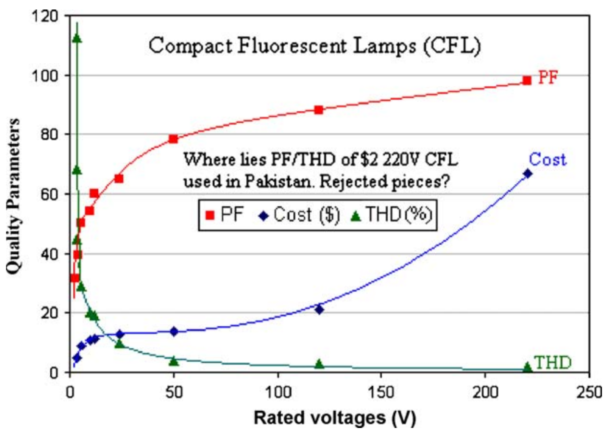


Fig. 13. CFL cost variation with PF and THD.

power factor is equal to the product of distortion and displacement factors. Customers may avoid high THD and low PF by purchasing equipment with built-in harmonic filters and PF correcting capacitors. It is easier to sort out at site rather than going for system level solutions. Utilities often deploy shunt connected 440 V (and higher) capacitors to improve PF. One of the capacitors connected to correct PF, filter harmonics or snubbing application may resonate (in series or parallel) at one of the harmonic frequency causing voltage or current magnification leading to blowing of fuses, overheating or capacitor busting. Harmonics cause overheating of transformers, motors, cables and malfunctioning of metering and protective devices. Even below resonance current flow increases inflicting utilities with rampant power losses. ANSI C 82.77 allows low power CFL with low PF and high THD but restricts high power CFL manufacturers to maintain PF > 0.90 and THD < 32%. Generally CFL PF and THD vary with rated voltage and power. CFL, LED, EEFL (LVD) and fluorescent tubes vendors THD and PF variations at rated voltage and power are shown in Fig. 12.

Generally CFL cost increases exponentially with low THD and high PF ballasts as shown in Fig. 13.

It is easier to mange PF correction at appliance level compared to system level. Basu and Bollen [41] estimated power factor correction costs of $15.25 and $ 85.18 for 200 W and 6 kW loads in homes and offices, respectively. Reactive power losses associated with poor power factor appliances in homes and offices are due to economic reasons. Measurements show CFL exhibit 120–137% current and 6.5% voltage THD which exceeds IEEE as well as IEC limits that allow up to 78% current and 6% voltage THD [42]. Recent research has found operational strategies to cancel harmonics of one type of equipment with harmonics of others through suitable load combinations [43–45]. It was demonstrated that PC and fluorescent tubes with magnetic ballasts can naturally cancel harmonics mutually [44]. Power quality engineers view low PF and high THD as a potent cancer that continues to undermine system performance during operation. Current and voltage THD at 11 kV level may be well within limits but inside these may exceed. A 0.13 A fluorescent lamp with magnetic ballast draws harmonic current >0.02 A but a 0.065 A fluorescent lamp with electronic ballast may draw 0.06, 0.05, 0.04 and 0.27 A current at different harmonics. Harmonic currents flow from loads towards grid but if some industry has installed PF correction capacitor then they might flow towards this site. Harmonics currents may flow towards PF correcting capacitors as well as grid depending upon the impedance involved. PF correction capacitors can minimize THD as THD reduction improves PF.

THD is measure of effective value of the harmonic components of a distorted waveform. Voltage THD may be expressed by

$$\mathrm{THD} = \frac{\sqrt{\sum_{h>1}^{h_{\max}} V_h^2}}{V_F} \tag{5}$$

where $V_1 = V_F$. RMS value of overall distorted waveform becomes

$$V_{\mathrm{RMS}}\left(\frac{V_{\mathrm{peak}}}{\sqrt{2}}\right) = \sqrt{\sum_{h=1}^{h_{\max}} V_h^2} \tag{6}$$

Or

$$V_{\mathrm{RMS}} = \sqrt{V_F^2 + \sum_{h>1}^{h_{\max}} V_h^2}$$

From Eqs. (5) and (6) one can write

$$V_{\mathrm{RMS}} = \sqrt{V_F^2 + V_F^2 \cdot \mathrm{THD}^2} \tag{7}$$

Or

$$V_{\mathrm{RMS}} = V_F\sqrt{1 + \mathrm{THD}^2}$$

For $V_h = V_F \times \mathrm{THD}$ from (5), we can rewrite (7)Or

$$V_{\mathrm{RMS}} = \sqrt{V_F^2 + V_h^2} \tag{8}$$

Similarly line RMS current

$$I_{\mathrm{RMS}} = \sqrt{I_F^2 + I_H^2} = I_F\sqrt{1 + \mathrm{THD}^2} \tag{9}$$

An industrial organization producing 40 A at fundamental frequency and 30 A at 3rd harmonic add to 50 A line I_{RMS} current by (5) rather than 70 A. Similarly 100 V harmonic voltage in 440 V system adds to 451 V by (4) rather than 540 V. Power quality engineers prefer to express the harmonic nuisance in terms of maximum load current (I_L) and total demand distortion (TDD) given by [35]

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} I_h^2}}{I_L} = \frac{\mathrm{THD}}{I_F I_L} \tag{10}$$

Or

$$\mathrm{THD} = I_F I_L \mathrm{TDD}$$

PF and THD correction requires capacitor banks and LC filters. Let us suppose a 250 kVA transformer powers a plant with 60%

current THD at lagging PF of 0.6. If plant demand varies from 83 to 100 kVA then capacitor bank size to improve PF restricting maximum demand (MD) below 85 kVA may be calculated as follows:

Calculate real active power (P_A)

$$P_A = \text{kVA}_{\text{MD}} \times \text{PF} = 100,000 \times 0.6 = 60 \ \text{kW}$$

Calculate RMS line current (I_{RMS})

$$I_{\text{RMS}} = \frac{\text{kVA}}{V_{\text{line}}\sqrt{3}} = \frac{100,000}{440\sqrt{3}} = 131 \ \text{A}$$

Calculate fundamental current I_{F} using (5)

$$I_F = \frac{I_{\text{RMS}}}{\sqrt{1+\text{THD}^2}} = \frac{131}{\sqrt{1+0.6^2}} = 112 \ \text{A}$$

Calculate harmonic current I_{H} using (5)

$$I_H = \sqrt{I_{\text{RMS}}^2 - I_F^2} = \sqrt{131^2 - 112^2} = 68 \ \text{A}$$

Calculate fundamental apparent power (kVA)

$$\text{kVA} = \sqrt{3} V_{\text{line}} I_F = \sqrt{3} \times 440 \times 112 = 85 \ \text{kVA}$$

Fundamental frequency reactive power (kVAr)

$$\text{kVAr} = \sqrt{\text{kVA} - \text{kW}} = \sqrt{85^2 - 60^2} = 60 \ \text{kVAr}$$

Due to large harmonic current it is not possible to improve PF to unity by addition of capacitors alone. We must add harmonic filters with harmonics injecting appliances such as ASD, rectifiers and computers. To achieve maximum power factor at expense of minimum MD, we can add 60 kVAr capacitor bank to neutralize all the reactive power. 60 kVAr capacitor bank installation to reduces the fundamental current (I_{F}) to

$$I_F = \frac{\text{kVAr}}{\sqrt{3} \times V_{\text{line}}} = \frac{60,000}{\sqrt{3} \times 440} = 78.7 \ \text{A}$$

Total line current after installing 60 kVAr capacitor bank (I_{RMS})

$$I_{\text{RMS}} = \sqrt{I_F^2 + I_H^2} = \sqrt{78.7^2 + 68^2} = 104 \ \text{A}$$

Maximum demand (MD) comes out to be

$$\text{kVA}_{\text{MD}} = \sqrt{3} \times V_{\text{line}} \times I_{\text{RMS}} = \sqrt{3} \times 440 \times 104 = 79 \ \text{kVA}$$

MDI meter allows margin up to 85 kVA therefore we can use 30 kVAr capacitor to cancel all the fundamental frequency reactive. New fundamental current I_{F} becomes

$$I_F = \frac{\sqrt{\text{kVAr}_r^2 + \text{kVAr}_C^2}}{\sqrt{3} \times V_{\text{line}}} = \frac{\sqrt{60^2 + 30^2}}{\sqrt{3} \times 440} = 88 \ \text{A}$$

Total line current after installing 30 kVAr capacitor bank becomes

$$I_{\text{RMS}} = \sqrt{I_F^2 + I_h^2} = \sqrt{88^2 + 68^2} = 111 \ \text{A}$$

Maximum demand (MD) comes out to be

$$\text{kVA}_{\text{MD}} = \sqrt{3} \times V_{\text{line}} \times I_{\text{RMS}} = \sqrt{3} \times 440 \times 111 = 84.75 \ \text{kVA}$$

It is close to minimum chargeable maximum demand of 85 kVA. The harmonic current remains unchanged in above calculations but resonance may occur. Harmonics can be filtered at 440 V level by installing LC filters with high current drawing appliances such as arc furnace, DC drives and computer server loads.

Suppose a 12 kVA load at lagging 0.75 PF has current THD of 25%. This facility is fed by 25 kVA transformer with 2% impedance. To raise the existing PF to 0.96 we need to design a star connected inductor and delta connected capacitor. To calculate specifications of this shunt connected LC filter we proceed as

Load reactive power demand at 75% PF may be calculated by

$$\text{kVAr} = \text{kVA}_{\text{load}} \sin(\cos^{-1}(0.75)) = 12,000 \times 0.66 = 7.94 \ \text{kVAr}$$

Reactive power demand for 95% PF would be

$$\text{kVAr} = \text{kVA}_{\text{load}} \sin(\cos^{-1}(0.96)) = 12,000 \times 0.28 = 3.36 \ \text{kVAr}$$

LC filter expected to compensate reactor power of (7.94–3.36) 4.58 kVAr. LC filter fundamental capacitive reactance (X_F) may be determined by

$$X_F = \frac{\text{kV}^2(1000)}{\text{kVAr}} = \frac{0.44^2 \times 1000}{4.58} = 42.27 \ \Omega$$

$$X_F = X_C - X_L$$

To tune filter to, let us say, 3rd harmonic ($3 \times 50 = 150$ Hz) the capacitor reactance will be

$$X_C = h^2 X_L = 9 X_L$$

LC filter capacitive reactance may be calculated using above two relations [14]

$$X_C = \frac{h^2 X_F}{h^2 - 1} = \frac{9 \times 42.27}{9-1} = 47.55 \ \Omega$$

Capacitor size may be calculated by

$$C = \frac{1}{2\pi f X_C} = \frac{1}{2\pi \times 50 \times 47.55} = 66.92 \ \mu\text{F}$$

Capacitor size for 440 V system would be estimated by

$$\text{Capacitor (kVAr)} = \frac{\text{kV}^2(1000)}{X_C} = \frac{0.44^2(1000)}{47.55} = 4 \ \text{kVAr}$$

LC filter reactance may be calculated from

$$X_L = \frac{X_C}{h^2} = \frac{47.55}{9} = 5.28 \ \Omega$$

Inductance of a 5.28 Ω reactance may be given by

$$L = \frac{X_L}{2\pi f} = \frac{5.28}{2\pi \times 50} = 16.80 \ \text{mH}$$

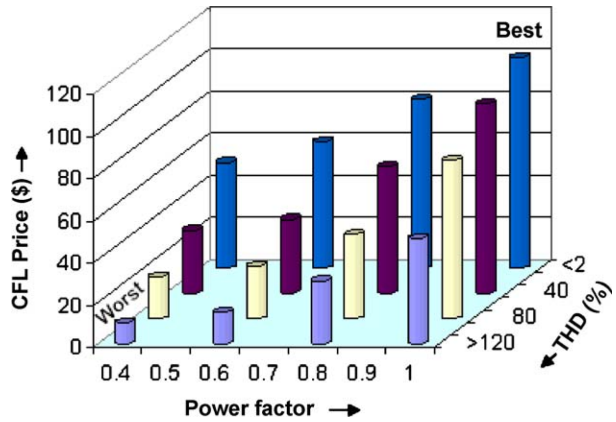


Fig. 14. CFL price variation with low to high PF and THD values.

Hybrid LC filters is connected in-parallel with the AC line, and constantly injects currents that precisely correspond to the harmonic components drawn by the load [45]. Harmonic conditioner attenuates current THD from 86% down to 28% within (IEEE Std.510-1992 recommended < 32% range), reduces 65% of the neutral current from 108 A down to 38 A and decreases 70% of the harmonic RMS current from 42 to 13 A. A single phase speed drive had 48 A phase current, 81% current THD, 42 A neutral, 0.77 PF requiring 10.6 kVA supply. When harmonics were mitigated using active harmonic filter the phase current reduced to 38 A, current THD to 3.4% (<32% IEEE limit), neutral current to 2.6 A, PF improved to 0.99 requiring rated power of 8.4 kVA. Power quality engineers guess low THD in low PF premises and high THD in high PF premises [18]. A CFL with high PF (>0.90) and low THD (32%) cost higher compared to low PF (<0.40) and high THD (≥200%) models. However, an intermediate PF (∼0.70) and THD (∼100%) or low THD with low PF or high THD with high PF compact fluorescent lamps (even LED and EEFL) may cost in between as shown in Fig. 14.

PF correction becomes difficult in the presence of harmonics that requires careful simulation before installation. Often long working systems become unstable due to resonance by minor modifications in loads. Power quality engineers recommend fresh simulation before installing capacitors for PF correction or any new inductive loads.

7. Conclusion

CFL usually produce current THD > 100% [1], which may be reduced by adding filters to CFL power supply. Simple CFL comes with high current THD and low power factor. An average CFL may have low current THD (100–130%) and moderate power factor (0.75) or high current THD (180–200%) and good power factor (>0.90) [46]. An excellent CFL may have low current THD (5–10%) and high power factor (0.95). Product of THD and PF can be adjusted as trade off. IEEE Std. 519 1992 limits voltage individual voltage harmonics <2–3% whilst voltage THD < 5% and current THD < 32%. Utilities offer incentives to customers for keeping current THD < 20%. Manufacturers have started producing expensive low THD and high PF CFL. Simulation studies have shown, in the presence of 115% current THD, voltage THD becomes 5% when CFL load exceeds 27–28% of lighting load. Similarly, in the presence of 55% current THD, the voltage THD becomes 5% when CFL load exceeds 47–48% of lighting load [5]. When current THD exceeds 143.9% the voltage THD becomes 2.5% and power factor drops to 0.54–0.64. CFL and LED lamps due to THD and PF problems require 30 VA power supply to operate a 15 W load. Incandescent lamps operate at zero THD and unity power factor but waste lot of power due to poor efficiency. A light lamp is characterized by the power required to operate, current THD, PF, output luminous flux, efficacy, efficiency, CRI, CCT and market price. This techno-economic study recommends to advise public to use LED or low current THD (<10%) high PF (>0.95) CFL lamps. Government and private sector may go for solar light fixtures and hybrid thermal photovoltaic systems. CFLs are more efficient than electric bulb but lesser efficient than EEFL, LED, and tubes. There is urgent need to increase awareness on LED lamps acceptance.

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